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1.	Your reference	WBH
2.	Patent application number *(The Patent Office will fill in this part)*	0221165.4 — 12 SEP 2002
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	Artemis Intelligent Power Limited Sanderson Building, Mayfield Road, Edinburgh EH9 3JL
	Patents ADP number *(if you know it)*	6593065001
	If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
4.	Title of the invention	FLUID-WORKING MACHINE AND OPERATING METHOD
5.	Name of your agent *(if you have one)*	J.Y. & G.W. Johnson
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Kingsbourne House, 229-231 High Holborn, London WC1V 7DP
	Patents ADP number *(if you know it)*	976001
6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	Country / Priority application number *(if you know it)* / Date of filing *(day / month / year)*
7.	If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application / Date of filing *(day / month / year)*
8.	Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* *a) any applicant named in part 3 is not an inventor, or* *b) there is an inventor who is not named as an applicant, or* *c) any named applicant is a corporate body.* *See note (d))*	Yes

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Continuation sheets of this form	
Description	8
Claim(s)	
Abstract	
Drawing(s)	3 +3 JMC

10. If you are also filing any of the following, state how many against each item.

Priority documents	
Translations of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature J W Johnson Date 12.9.02

12. Name and daytime telephone number of person to contact in the United Kingdom

Mr William Hanson
020 7405 0356

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FLUID-WORKING MACHINE AND OPERATING METHOD

This invention relates to a fluid-driven (motor) and/or fluid-driving (pump) machine having a plurality of working chambers of cyclically changing volume and valve means to control the connection of each chamber to low- and high-pressure manifolds. The invention also relates to a method of operating the machine.

The invention has particular reference to non-compressible fluids, but its use with gases is not ruled out. It has particular reference to machines where the at least one working chamber comprises a cylinder in which a piston is arranged to reciprocate, but its use with at least one chamber delimited by a flexible diaphragm or a rotary piston is not ruled out.

With most fluid working machines the fluid chambers undergo cyclical variations in volume following a sinusoidal function. Flow rectifying seating valves, allowing fluid to be admitted and exhausted from the working chamber, are electro-magnetically actuated such that pumping and motoring strokes can be achieved. The chamber can be left to idle by holding the valve, between the working chamber and the low-pressure sump, in the open condition.

A shaft position sensor is used to provide the micro-controller with chamber phase information while flow or pressure demand inputs influence the rate at which chambers are pumped, motored or left idle. The micro-controller drives semiconductor switches, such as field effect transistors, which in turn actuate the valves connecting the chambers to either the high-pressure manifold or low-pressure sump.

Experience shows that varying the timing of the valves, such that portions of the stroke are disabled, in order to vary machine output creates a significant amount of audible and fluid borne noise.

The development of electro-magnetically actuated, seating valves working in conjunction with a varying fluid chamber volume, such as described in EP-A-361927 and EP-A-0494236, permitted the output of a fluid working machine having a plurality of

working chambers to be varied, in a time averaged way, by the rate of selection of whole chambers as they became available at the ends of each expansion or contraction cycle.

EP-A-0361927 described the use of this technique for a pump in which shaft power was controllably converted to fluid power. EP-A-0494236 continued the concept and, by introducing a new mechanism for actuating the valves in a motoring cycle, developed the machine to allow a controllable bi-directional energy flow.

A multi-piston hydraulic machine according to EP-A-0494236 is shown in schematic section in Figure 1. In the side wall of each cylinder 11 is a poppet valve 13 communicating with a high-pressure manifold 14 and in the end wall of each cylinder is a poppet valve 15 communicating with a low-pressure manifold 16. The poppet valves 13 and 15 are active electromagnetic valves controlled electrically by a microprocessor controller 20 feeding control signals, via optoisolators 21, to valve-driving semiconductors 22.

Pistons 12 act on a drive cam 23 fast to an output shaft 24, the position of the cam 23 being sensed by an encoder 25.

The controller 20 receives inputs from the encoder 25, a pressure transducer 26 (via an analogue to digital converter 27) and via a line 28 to which a desired output speed demand signal can be applied.

The poppet valves 13, 15 seal the respective cylinders 11 from the respective manifolds 14, 16 by engagement of an annular valve part with an annular valve seat, a solenoid being provided to magnetically move each said valve part relative to its seat by reacting with ferromagnetic material on the said poppet valve, each said poppet valve having a stem and an enlarged head, the annular valve part being provided on the head and the ferromagnetic material being provided on the stem.

In EP-A-361927 and EP-A-0494236, whole chambers were selected on the basis that valve actuation could be done during the instances of near zero flow. It was considered that delayed closure of valves, occurring during times of significant flow, such that part of the

chamber displacement could be rejected, would result in extremely high rates of change of flow and pressure, which in turn would generate noise.

The approach of whole chamber selection works well for high flow rates, seeing as the mechanical payload, driven by this type of system, typically has a large momentum such that variations in flow energy cause relatively small changes in its velocity and, therefore, acceleration.

However, in practice it was found that whole chamber selection during times of low flow demand resulted in large flow variations, seeing as the fluid machine was idle for long instances between active chambers. When a payload has a small velocity, as it will when the actuating flow is low, the momentum will also be minimal. If each actuated chamber is considered to be delivering a quantum of energy to the payload, then the change in velocity will be significantly higher when the initial energy is low.

The invention seeks to address this problem such that a smooth actuating response can be achieved at the payload.

The present invention provides a fluid-working machine having a plurality of working chambers of cyclically changing volume, a high-pressure fluid manifold and a low-pressure fluid manifold, at least one valve linking each working chamber to each manifold, and electronic sequencing means for operating said valves in timed relationship with the changing volume of each chamber, wherein the electronic sequencing means is arranged to operate the valves of each chamber in one of an idling mode, a partial mode in which only part of the usable volume of the chamber is used, and a full mode in which all of the usable volume of the chamber is used, and the electronic sequencing means is arranged to function in at least one combination of modes comprising partial mode operation of at least one but not all of said chambers.

In a most preferred embodiment of the invention, the partial mode comprises the use of only a small fraction of the usable volume of the chamber.

Preferably, the machine is operable as both a pump and a motor, each chamber having five selectable modes, namely idling mode, partial motoring mode, full motoring mode, partial pumping mode and full pumping mode.

Preferably, the working chambers comprise cylinders in which pistons are arranged to reciprocate. If so, the partial pumping mode preferably comprises closing the valve linking the cylinder to the low-pressure manifold and opening the valve linking the cylinder to the high-pressure manifold a small fraction in advance of the top dead centre position of the piston. The partial motoring mode preferably comprises closing the valve linking the cylinder to the high-pressure manifold and opening the valve linking the cylinder to the low-pressure manifold a small fraction after the top dead centre position of the piston.

If valve actuations are delayed in this way to almost the end of the stroke, then the rate of change of chamber volume will be at an acceptably low level to permit valve actuation. This means that a small fraction of a whole cylinder can also be selected by the controller to add to the machine's output. The range over which this is practicable is limited by stability of valve operation, on the low flow end, and by machine noise on the higher end. In practice this range is sufficiently limited that it is considered to have added two distinct, low-flow, modes to the three-mode machine, providing the above-mentioned range of five modes to the controller at any time that a chamber comes to the position at which an action can be taken.

The invention also provides a method of operating a fluid-working machine having a plurality of working chambers of cyclically changing volume, a high-pressure fluid manifold and a low-pressure fluid manifold, at least one valve linking each working chamber to each manifold, comprising operating the valves of each chamber in one of an idling mode, a partial mode in which only part of the usable volume of the chamber is used, and a full mode in which all of the usable volume of the chamber is used, wherein at least one but not all of said chambers is operated in the partial mode.

Preferably, the method comprises selecting the number of chambers to be operated in each of said modes according to an algorithm depending on the actual and required power output of the machine.

In a most preferred embodiment of the invention, the partial mode comprises the use of only a small fraction of the usable volume of the chamber.

The method may comprise a preliminary step of selecting whether to operate the machine as a pump or a motor, and choosing the algorithm accordingly.

In order that the invention may be more readily understood, embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a schematic sectional view of the known fluid-working machine described above which can be adapted according to the present invention;

Figure 2 is a pulse and timing diagram for the adapted machine when operating as a pump; and

Figure 3 is a pulse and timing diagram for the adapted machine when operating as a motor.

The machine described in EP-A-0494236 and shown in Figure 1 can be adapted to provide a machine according to the invention without additional hardware to create a part-stroke mode. The adaptation consists of increasing the functionality and complexity of the microprocessor control algorithms.

At any one instant there are four possible states for any of the chambers 11: (1) intake from the low-pressure manifold, (2) exhaust to the low-pressure manifold, (3) intake from the high-pressure manifold and (4) exhaust to the high-pressure manifold.

Let "mode" denote a repeating cyclic sequence of transitions from one of these states to another. There are five distinct modes: full stroke pumping, part stroke pumping, full stroke motoring, part stroke motoring, and idling.

The difference between full and part stroking modes is the phase angle at which transitions are made from one of these states to the other relative to bottom and top dead centre of piston movement:

Figures 2 and 3 are timing diagrams for pumping and motoring respectively, showing piston position, the states of electronic gates for controlling the high-pressure and low-pressure valves, the positions of those valves and the cylinder pressure, all plotted against time. The shaded portions indicate active portions of the piston stroke.

In the case of full stroke pumping mode, shown at the bottom right of Figure 2, the transition from state (1) to state (4) happens at or near to bottom dead centre causing the full cylinder volume to be pumped into the high-pressure manifold.

In the case of part stroke pumping mode, shown in the top half of Figure 2, the transition from state (1) to state (4) happens a small fraction in advance of top dead centre, causing only a small fraction of the cylinder volume to be pumped into the high-pressure manifold.

In both pumping modes the transition from state (4) to state (1) happens at or near to top dead centre.

In the case of full stroke motoring mode, shown in the bottom half of Figure 3, the transition from state (3) to state (2) happens at or near to bottom dead centre, causing the full cylinder volume to be inducted from the high-pressure manifold. The transition from state (2) to state (3) happens at or near to top dead centre.

In the case of part stroke motoring mode, shown in the top half of Figure 3, the transition from state (3) to state (1) happens a small fraction after top dead centre, causing only a small fraction of the cylinder volume to be inducted from the high-pressure manifold. The transition from state (1) to state (2) happens at bottom dead centre. The transition from state (2) to state (3) happens at or near to top dead centre of piston movement.

In the case of idling mode, shown at the bottom left of Figure 2, the transition from state (1) to state (2) happens at bottom dead centre of piston movement. The transition from state (2) to state (1) happens at top dead centre of piston movement.

A sequence of mode changes on successive machine cycles mixing pumping or motoring modes with idling modes allows the time averaged effective flow rate into and out of the high-pressure manifold to be infinitely varied between full pumping flow, zero flow, and full motoring flow.

Since the machine has a plurality of chambers, and each chamber may be set in any of five states, then many instantaneous configurations are possible. Some physical limitations exist however, in that a chamber which has been selected for full-stroke operation cannot, on the same part of the cycle, be selected for part-stroke use.

Control Over the Full Range of Output

The flow control method described in EP-A-0361927 and EP-A-0494236, which used a displacement demand during an accounting interval, combined with a look-ahead algorithm, can be extended for use with the five-mode machine of the invention. At zero flow the machine is in a permanent idling mode. At low flows the operation sequence is composed of partial stroke and idling modes with the fraction of these two modes reflecting the demand level. As flow demand increases, the fraction of partial stroke modes relative to idling modes increases. At some stage the controller begins to use occasional full stroke modes interspersed with idle and part-stroke modes to continue the ramping up of flow. Starting from the other end of the range at full flow output, the machine is in permanent full stroke mode. As flow demand drops, idling modes are interspersed with full stroke modes, leaving regular gaps in the flow rate. This process continues until the ratio of full stroke modes to idling modes falls below a fixed or variable threshold, at which point the controller begins mixing idle modes, part stroke modes and full stroke modes. The mixture of modes of operation, where three modes are being employed in a sequence, is tailored for the smoothest flow result and/or the most seamless change in audible noise and/or minimal pressure ripple and/or optimum actuator motion. Several algorithms are possible to mix states over this range.

In the case of pressure control, the decision on the mixture of modes in the sequence is based upon some function of the error between the measured and demanded pressure, and optionally the time history of past system responses to past pumping/motoring decisions allowing for adaptive techniques to minimise pressure fluctuation in response to varying system parameters.

In the case of position or velocity control of an hydraulic actuator, the decision on the mixture of modes in the sequence is based upon some function of the error between the measured and demanded position or velocity, and optionally the time history of past system responses to past pumping/motoring decisions allowing for adaptive techniques to minimise position or velocity error in response to varying system parameters.

As alternatives to electromagnetic valves, valves operating by piezoelectric or magnetostrictive means could be used in the invention.

All forms of the verb "to comprise" used in this specification have the meaning "to consist of or include".

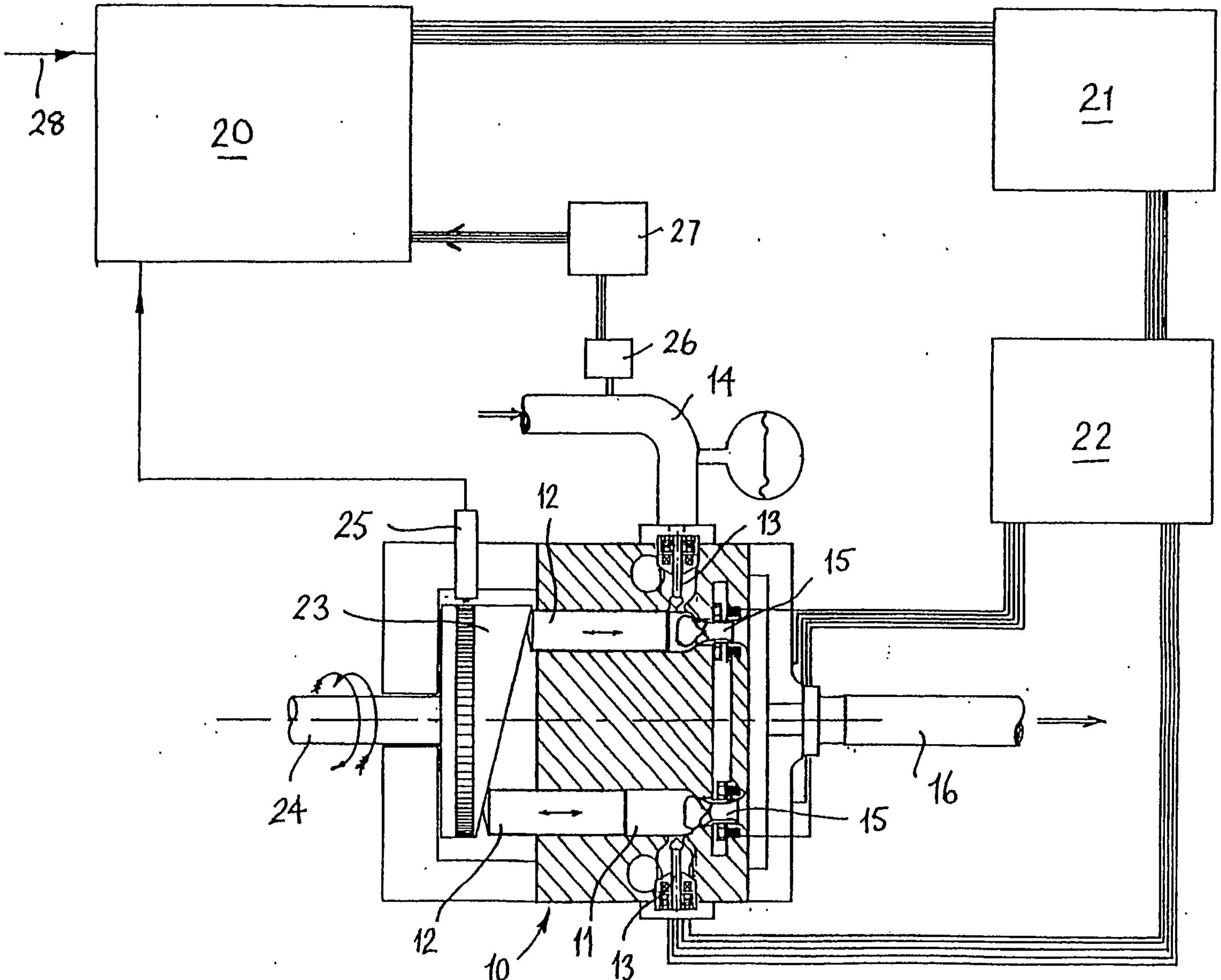

FIG.1

(Prior Art)

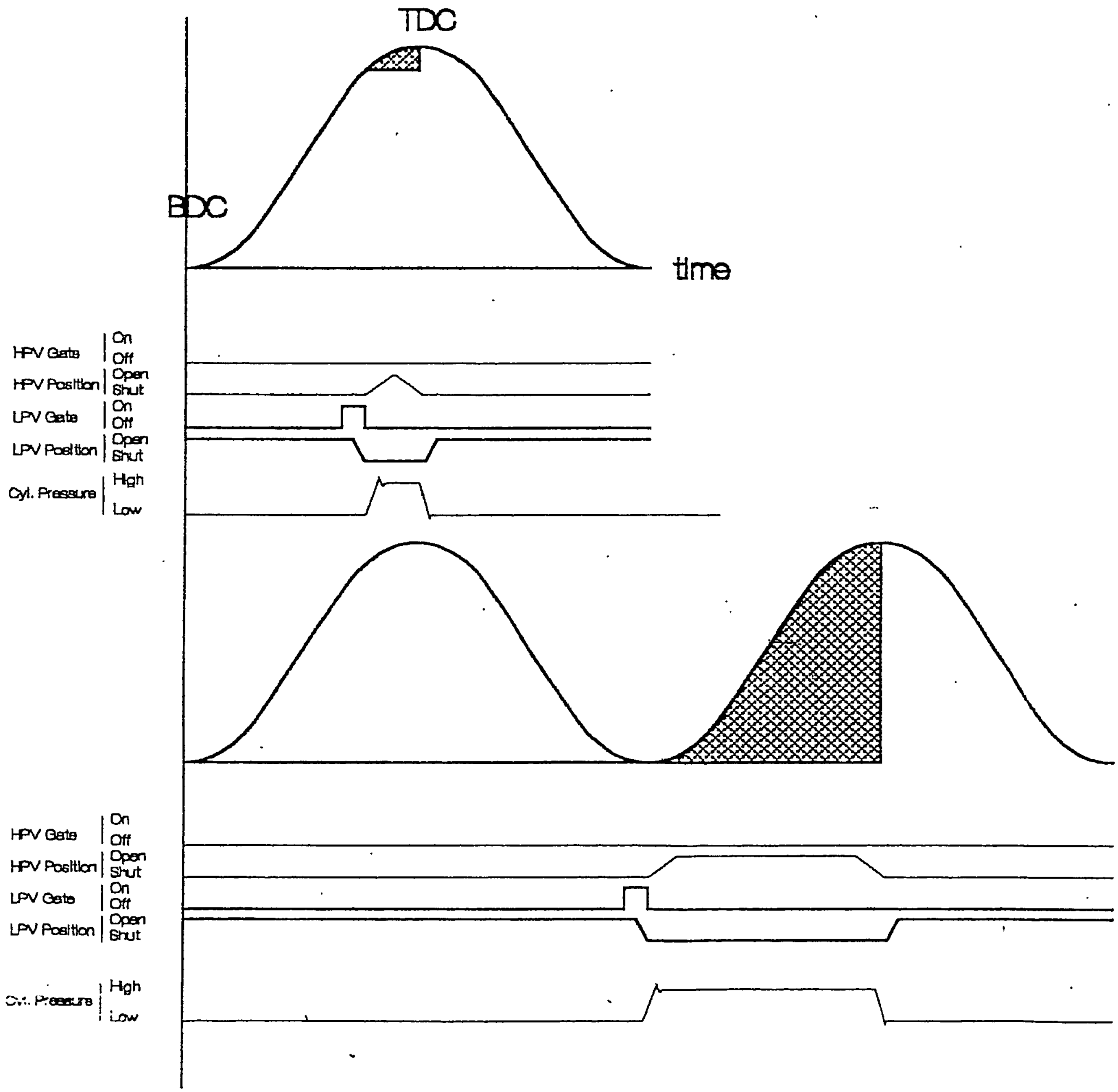
TDC
BDC
time
HPV Gate
On
Off
HPV Position
Open
Shut
LPV Gate
On
Off
LPV Position
Open
Shut
Cyl. Pressure
High
Low

Fig. 2

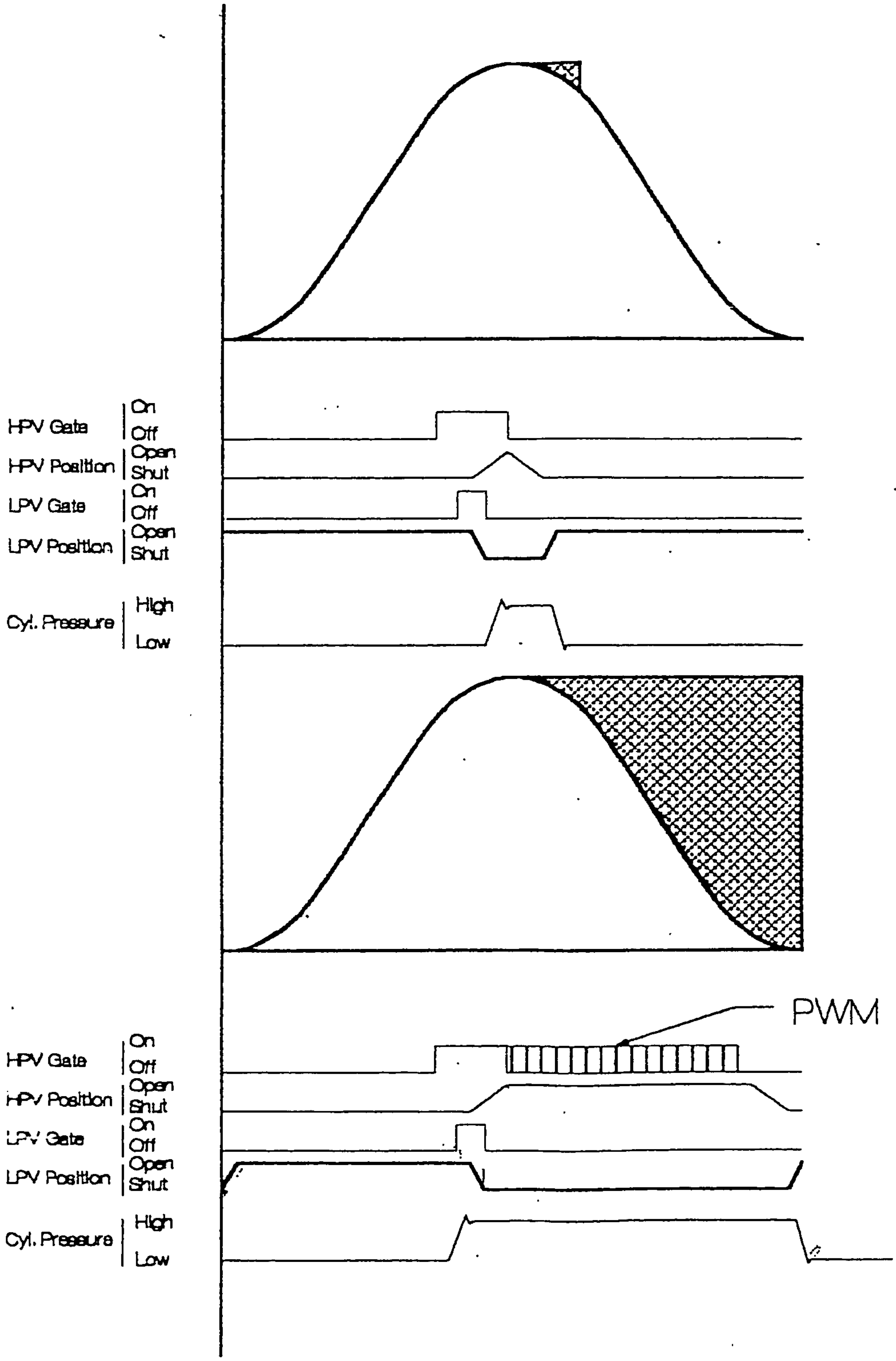
HPV Gate
On
Off
HPV Position
Open
Shut
LPV Gate
On
Off
LPV Position
Open
Shut
Cyl. Pressure
High
Low
PWM
HPV Gate
On
Off
HPV Position
Open
Shut
LPV Gate
On
Off
LPV Position
Open
Shut
Cyl. Pressure
High
Low

Fig. 3

PCT Application
GB0303949